A DETERMINATION OF THE ELECTRICAL

PROPERTIES OF SOIL IN THE STATE OF GEORGIA

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A THESIS

Submitted in partial fulfillment
of the requirements for the Degree
of Master of Science in Electrical Engineering

by

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Atlanta, Georgia
1947

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Approved:

Date Approved by Chairman Feb. 5, 1947

ACKNOWLEDGMENT

I wish to express my sincerest appreciation to Professor M. A. Honnell, not only for his suggestion of the problem, but also for his most valuable aid and guidance in its prosecution.

DEFINITIONS OF SYMBOLS USED

C - Capacitance of the coaxial space in which the dielectric is contained

C_o - The remaining capacity of the earth cell, excluding the dielectric space, but including all other capacitances

C_t - Total capacitance of the earth cell

ϵ - Dielectric constant

σ - Conductivity

a - Outer radius of the inner conductor of the concentric cylindrical condenser

b - Inner radius of the outer conductor of the concentric cylindrical condenser

s - Length of the dielectric space of the cylindrical earth cell

X_a - Reactance of the auxiliary condenser

X_e - Reactance of the auxiliary condenser and the earth cell in parallel

R_e - Resistance of the auxiliary condenser and the earth cell in parallel

X_s - Equivalent series reactance of the earth cell alone

R_s - Equivalent series resistance of the earth cell alone

X_p - Equivalent parallel reactance of the earth cell alone

R_p - Equivalent parallel resistance of the earth cell alone

C_p - Equivalent parallel capacitance of the earth cell alone

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

A DETERMINATION OF THE ELECTRICAL PROPERTIES OF SOIL IN THE STATE OF GEORGIA

INTRODUCTION

A considerable amount of pioneer work in the study of the transmission of electro-magnetic waves over, or through, a conducting dielectric was included in the classical researches of Clerk Maxwell, Oliver Heaviside, and Sir J. J. Thomson. After it had been demonstrated that electric waves could be transmitted to appreciable distances over the earth's surface, much attention was devoted to the effect of the earth on radio, or wireless, communication. Sir Oliver Lodge, in 1899, demonstrated the application of classical electro-magnetic theory to this problem. A mathematical investigation of the propagation of electric waves along the earth's surface was published by A. Sommerfeld in 1909. Since that time a great number of men have become interested in the properties of the earth, and the effect such properties have upon wave propagation. These studies have included the variation of the dielectric constant and conductivity with frequency and with the moisture content and temperature of the soil.

In radio communication the electrical properties of the earth enter directly into the design of a transmitting installation. The conductivity and dielectric constant are dominating factors in determining the effective service area of broadcast stations. The efficiency of a good receiving station depends on good conductivity of the ground on which it is erected. The increasing use of shorter and shorter wave lengths, with the consequent increase in the attenuation of ground waves, has emphasized the importance of obtaining accurate knowledge of the electrical properties of ground. The determination of ground resistance, however, is not an easy matter since frequency determines to what extent the ground acts as a conductor and to what extent as a condenser. The conductivity and dielectric constant of the soil vary widely with frequency. A general statement that the ground acts toward electro-magnetic waves as an insulator (very high resistance) is not correct. Also, the general statement that it behaves as a good reflector is true only for a certain frequency range. Actually, both the conductivity and the dielectric constant must be taken into account to explain its behavior, especially when wave propagation along the ground is of interest.

In view of the importance attached to the electrical properties of soil and because so little work of this nature has been done in the state of Georgia, it seemed that the results of a study of this kind would be most interesting and useful to the radio engineers of this section. As far as the author has been able to ascertain from the literature, no one has attempted to obtain measurements of the electrical properties of soil over a wide range of frequencies and present the information obtained in a clear and usable form. It is, therefore, the purpose of the writer to ascertain the dielectric constant and conductivity of a number of typical samples of Georgia soil over a frequency range from 600 kilocycles to 50 megacycles, and to present the results in tabular and graphical form.

THE METHOD AND TECHNIQUE USED

Several methods are indicated for the determination of the electrical properties of soil. The direct method consists of measurements made on buried parallel wires or on a coaxial cylindrical condenser in which the soil being tested forms the dielectric. In the indirect method the forward tilt of the wave front with respect to the normal to the ground is used for the determination. The direct method has been selected as the best method for the work undertaken in this paper because all of the measurements were to be made in the laboratory. This method is simpler and more convenient if an earth cell is used. The soil under investigation in the laboratory formed the dielectric between the plates of a coaxial condenser, and the effective capacitance and resistance were measured at frequencies from 600 kilocycles to 50 megacycles.

The validity of the method selected was shown by R. L. Smith-Rose.[1] By a series of preliminary measurements Smith-Rose showed that reliable results could be obtained which were independent of the size and shape of the fixed condenser in which the soil was packed as the dielectric. C. B. Feldman used such a method in his labora-

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[1] R. L. Smith-Rose, "Electrical Measurements of Soil with Alternating Currents", Journal of the Institution of Electrical Engineers, Vol. 75, 1934. pp. 221 - 237.

tory measurements on soil. Feldman used a cylindrical test condenser and determined the conductivity and dielectric constant from measurements of effective resistance and capacitance made with a Q-Meter.[2] In the treatment by the author the measurements were obtained using a radio frequency bridge.

Since this method had been selected, it was then necessary for the author to design an earth cell to contain the soil sample to be measured. A concentric cylindrical condenser (see Figures 1 and 2) was made using a piece of brass tubing for the outer conductor and a solid brass rod for the inner conductor. The center conductor was supported by several polystyrene discs, and a brass plate closed the lower end of the condenser. Banana plugs were attached to the conductors to serve as leads, and a removable brass cap was fitted to close the upper end of the condenser. This having been done, it was necessary only to locate a convenient spot in the laboratory and set up the apparatus.

The apparatus was set up inside a small booth that was completely enclosed with copper wire mesh screening to shield the apparatus from other equipments in the room. The apparatus used consisted of the following equipments:

(1) Radio frequency bridge, General Radio Co. type

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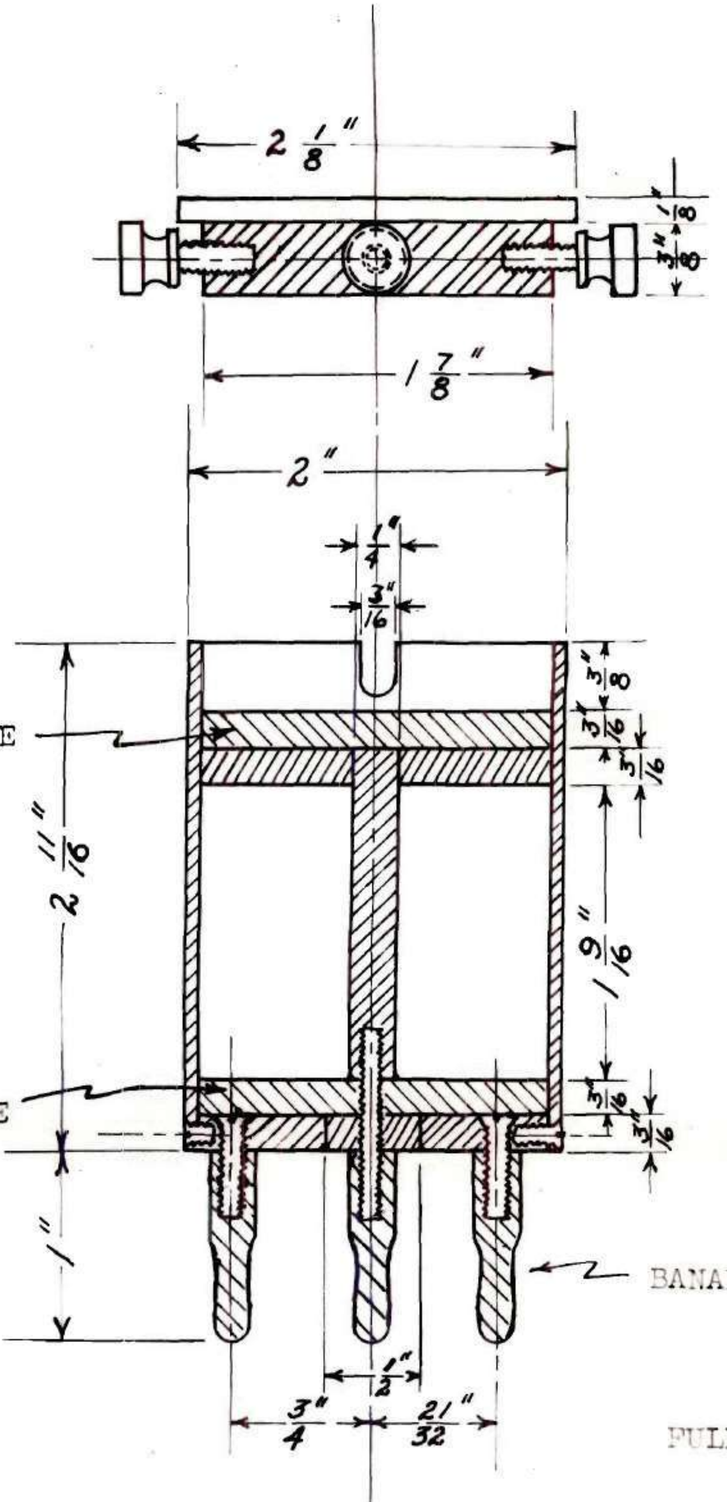
[2] C. B. Feldman, "The Optical Behavior of Ground for Short Radio Waves", <u>Proceedings of the Institute of Radio Engineers</u>, No. 6, Vol. 21, 1933. pp. 764 - 801.

FIGURE 1



FULL SCALE

ALL SCREWS 6/32

EARTH CELL

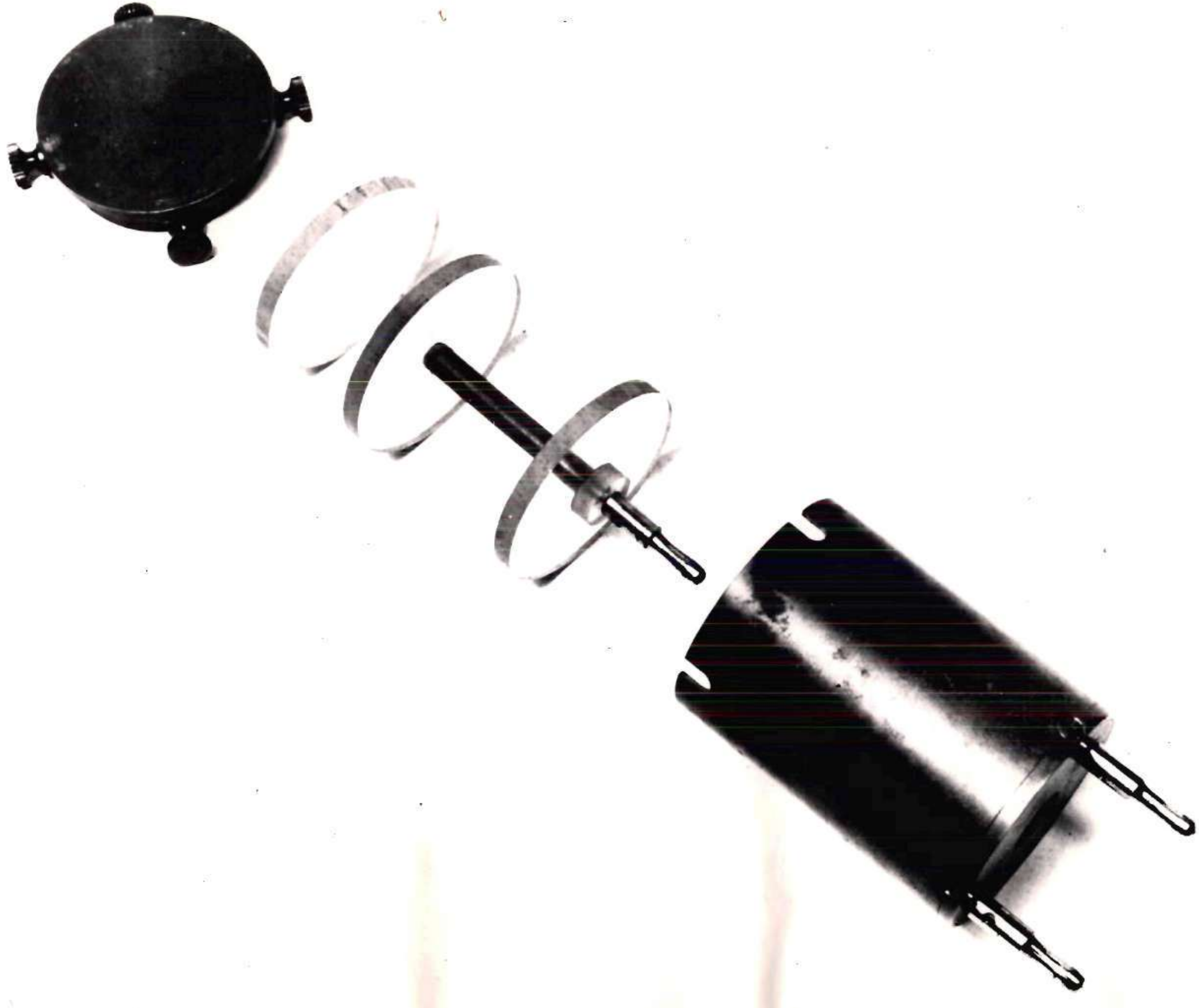


FIGURE 2
EARTH CELL

916-A

(2) Radio frequency bridge, General Radio Co. type 516-C (used for check measurements only)

(3) Radio receiver, Hallicrafters "Sky Challenger" (used in frequency range from 600 kcs. to 20 mcs.)

(4) Radio receiver, Hallicrafter "U.H.F. Communication Receiver" Model S-36 (used in frequency range 20-50 mcs.)

(5) Signal generator, Triplet Model 1632 (used in frequencies from 600 kcs. to 10 mcs.)

(6) Signal generator, Ferris "Microvolter" Model 18-FS No. 422 (used for frequency range from 20-50 mc.)

A signal generator was connected to the input bridge terminals, and a receiver was used as a detector. Pictures of this arrangement are shown in Figures 3 and 4, and a block diagram of the set up appears in Figure 5. The earth cell was plugged into the "unknown" terminals of the bridge, and its effective reactance and resistance were measured. For frequencies below 30 megacycles the null was detected with a pair of earphones. This null was very sharp for frequencies below 20 megacycles. For frequencies above 20 megacycles, however, the null was detected with an output meter. The signal generator was shielded from the bridge and the receiver by a well-grounded piece of galvanized wire mesh. Great care was taken to see that each piece of equipment

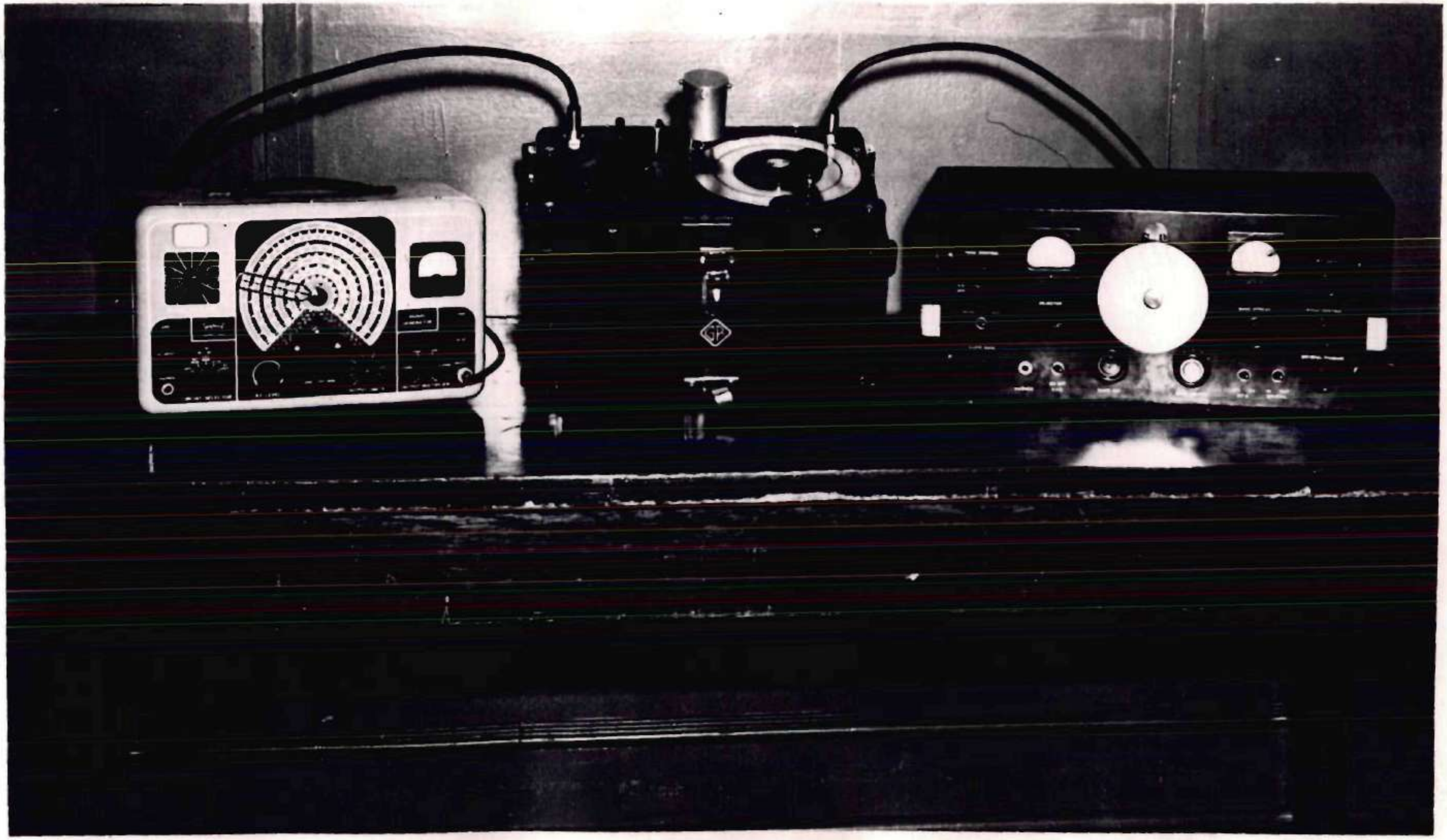


FIGURE 3
FIRST SET UP

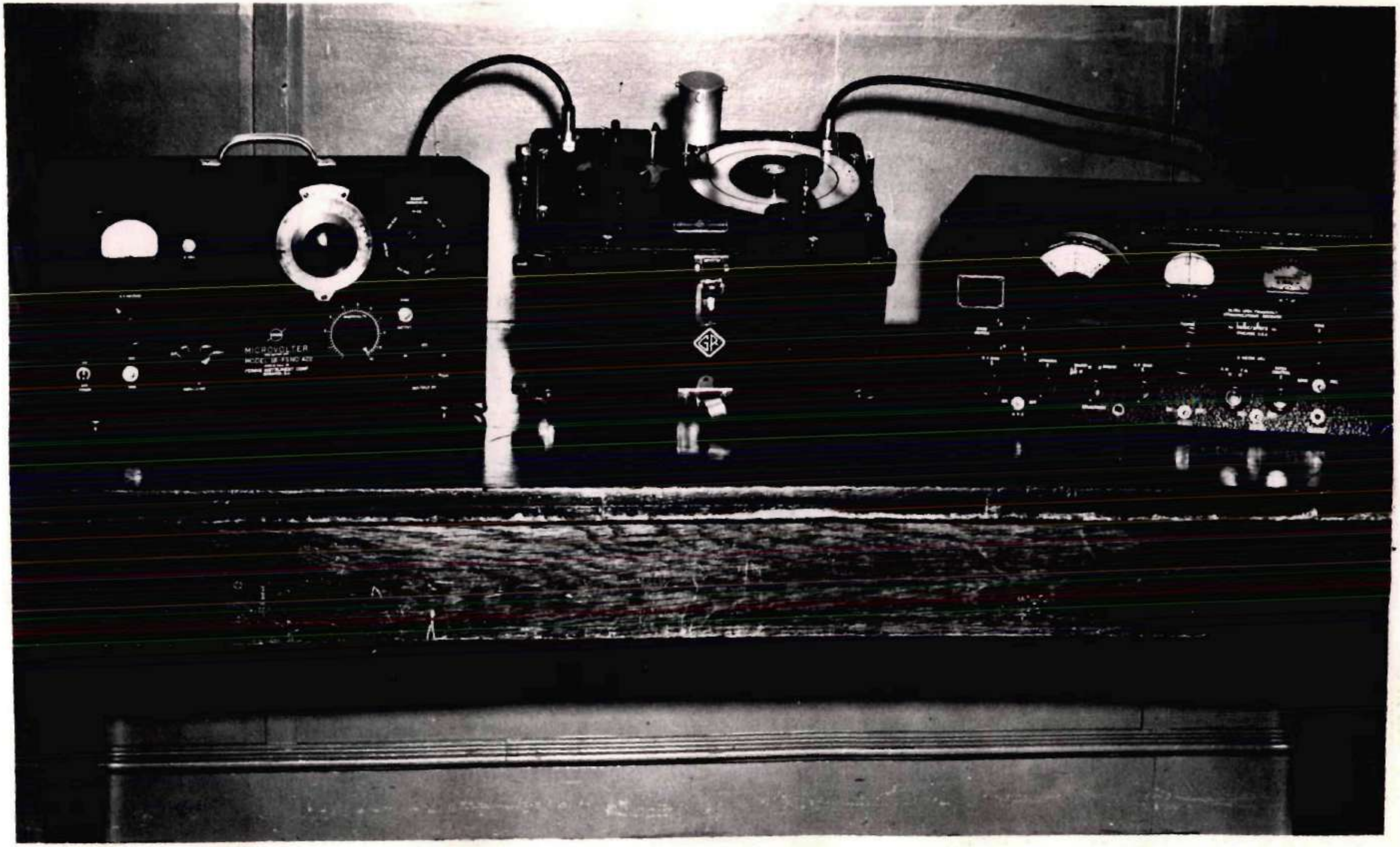


FIGURE 4
SECOND SET UP

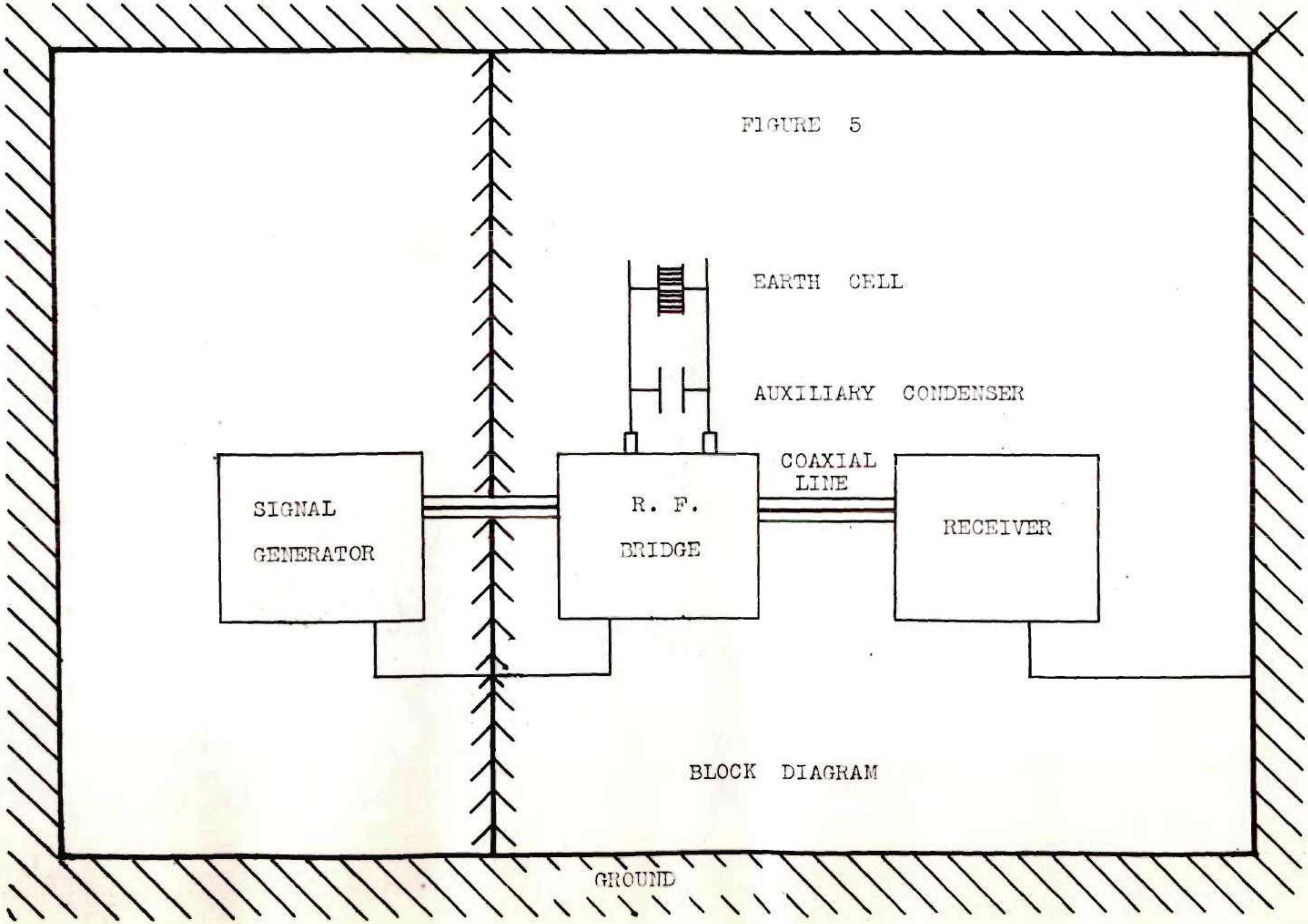


FIGURE 5

BLOCK DIAGRAM

was well grounded. Preliminary measurements made on the earth cell using paraffin as the dielectric (see appendix) showed the validity of the method used. The accuracy of this method was also checked using another bridge and by measuring the effective resistance and reactance of known standards (see appendix). When soil was used as the dielectric and measurements were made, an effort was made to simulate natural conditions when the soil was packed into the cell.

DISCREPANCIES AND ERRORS IN METHOD USED

As the frequency was increased, the position of the observer's body affected the measurements, and considerable care was taken to prevent the resultant errors. While taking measurements the observer took care to remain in one place and to reduce to a minimum the movements necessary to take readings.

Another source of difficulty lay in the reading of the reactance dial of the radio frequency bridge. There is no vernier dial on the equipment to assist the observer in reading this dial. The scale of the reactance dial is semi-logarithmic, and there are few scale divisions at the high end. This scale is so crowded together at the high end that it could not be accurately read. It was difficult to obtain a balance at a frequency of 30 megacycles because of the low sensitivity of the receiver. For this reason measurements at this frequency are not reliable.

Since it was thought that the cell and its dielectric sample might be voltage sensitive, i.e., that its reactance or resistance might vary with the voltage applied, care was taken to see that the output of the signal generator remained constant for all measurements. The cell, however, did not appear to be particularly sensitive to voltage as no measurable difference could be detected, when the voltage was varied. When a very sharp null could be detected and the voltage was changed the null would be lost, but the null could be regained with an imperceptible movement of the dial. It is believed that the inability of the observer to read the dial with great accuracy obscured any error due to the variation of the input voltage.

Due to thelimited range of the bridge in the measurement of reactance, 0 - 5000 ohms, an auxiliary mica capacitance of about 50 mmf. was connected in parallel with the earth cell. The use of this capacitor made it unnecessary to make corrections for the reactance and resistance of the bridge leads, but it introduces another source of error because the incremental difference in the measured values were a smaller percentage of the total than they would be otherwise.

It was noted that it became exceedingly difficult to measure any dielectric loss at the higher frequencies (note Tables 6 - 9), however this is easily explained.[3] This resistance is understood to be the small resistance, R_s, which may be imagined in series with the pure capacitance, C_s, of a condenser to account for all of its losses. A very high resistance in parallel with the pure capacitance may also be used in accounting for the losses. The values for the pure capacitance for the series and the parallel resis-

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[3]August Hund, High Frequency Measurements. New York and London: McGraw-Hill Book Company, 1933. p. 286.

tances are not exactly alike, but are nearly so in most cases. It is the action of a high ohmic parallel loss resistance and that of a low series resistance which is utilized in the determination of condenser resistance. The series resistance, R_s, also known as the equivalent resistance, if multiplied by the capacitive admittance, ωC, for many condensers practically gives a constant value for the entire high frequency range and is approximately equal to the low frequency value of ωCR_s. The constancy of ωCR_s explains why it is so difficult to accurately determine the equivalent resistance, R_s, at a high frequency. As the frequency is increased, R_s must decrease inversely with the first power of the frequency. Thus resistance values of a fraction of one ohm may occur for the upper high frequency range. Even a high loss condenser may have an equivalent resistance that is very low at radio frequencies. For this reason it is increasingly difficult to determine the conductivity at the higher frequencies of this undertaking.

DEVELOPMENT OF A METHOD OF CALCULATIONS

A number of assumptions have been made to simplify the work undertaken in this paper. Since the banana-plug leads were so short the effect of these leads has in part been neglected. Because a form of substitution method was used, due to the changing of the cell dielectric from air to soil, any error due to this assumption would be balanced out.

All of the measured loss has been assumed to be dielectric loss because no other losses were detected. It was assumed that the lines of current flow in the dielectric coincide with the lines of electric flux in the cell and that they are entirely radial in the dielectric space regardless of the dielectric used. The empty cell was assumed to be a pure capacitance; while this is actually physically unrealizable, no detectable difference was noted. This assumption greatly simplifies the calculations, but introduces an error, especially at the higher frequencies.

The assumptions underlying the equations used for computation of the dielectric constant and of the conductivity are valid if the high-frequency distribution of current in the sample is the same as the low-frequency distribution, i.e., if the skin effect is small.

The concentric cylindrical condenser may be considered as two condensers in parallel. The first of these condensers, C, was assumed to be the capacitance of the dielectric space, the volume containing the dielectric. The capacitance of this condenser is calculated using the coaxial formula,[4]

$$C = \frac{0.0388 \ \epsilon}{LOG_{10} \frac{b}{a}} \ \mu f/mile$$

where "b" is the inner radius of the outer conductor and "a" is the outer radius of the inner conductor. For the particular cell under examination this formula gives a value of C= 1.09 mmf, when air is the dielectric. The second of these parallel condensers, C_o, includes all other capacitances of the earth cell. We may then assume that the total capacitance of the earth cell at any time is given by

$$C_t = C_o + \epsilon C$$

Using the formula for resistance appearing in The Engineers' Manual by Ralph G. Hudson, an expression for the conductivity is developed.[5]

$$R = \frac{\rho}{2\pi S} \ LN \frac{b}{a}$$

where ρ is in ohms per cubic centimeter. Since the literature is concerned not with resistivity per cubic centi-

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[4]R. G. Hudson, The Engineers' Manual. New York and London: John Wiley and Sons, 1939. 340 pp.

[5]Ibid. p. 207.

meter but with conductivity in electro-magnetic units, this formula is converted to

$$R = \frac{10^{-9}}{2\pi\sigma S} \quad LN \frac{b}{a}$$

which for this particular cell reduces to

$$\sigma = \frac{1}{R} \times 0.808 \times 10^{-10} \quad EMU$$

The following formulae are given in the instruction manual for the General Radio, Radio Frequency Bridge, type 916-A, for the case in which an auxiliary condenser is used.

$$R_s = \frac{R_e\,(X_a)^2}{(R_e)^2 + (X_e - X_a)^2}$$

$$X_s = -\,\frac{X_a\left[(R_e)^2 + X_e(X_e - X_a)\right]}{(R_e)^2 + (X_e - X_a)^2}$$

In the above formulae, if X_a, or X_e, is capacitive the numerical value substituted should have a negative sign.

Since calculations of conductivity and dielectric constant were made from the equivalent parallel values and not from the equivalent series values, the following formulae were developed for the conversion. Starting with the equation for the impedance of the series representation and equating it to the expression for the parallel equivalent we have

$$R_s - jX_s = \frac{-jX_p R_p}{R_p - jX_p}$$

By rationalizing and equating the corresponding resistive terms and the corresponding reactive terms, the following expressions are obtained.

$$R_p = \frac{(R_s)^2 + (X_s)^2}{R_s}$$

$$X_p = \frac{(R_s)^2 + (X_s)^2}{X_s}$$

The value of C_o for any frequency is obtained from the measured capacitance of the empty cell (see Table I).

CALCULATIONS FOR DRY RED CLAY AT ONE MEGACYCLE

FOR DATA SEE TABLE III

$$R_s = \frac{R_e(-X_a)^2}{(R_e)^2 + (X_a - X_e)^2} \qquad X_s = \frac{X_a\left[(R_e)^2 - X_e(X_a - X_e)\right]}{(R_e)^2 + (X_a - X_e)^2}$$

$$R_s = \frac{62.5(-2720)^2}{(62.5)^2 + (2720-2360)^2} \qquad X_s = \frac{2720\left[(62.5)^2 - 2360(2720-2360)\right]}{(62.5)^2 + (2720-2360)^2}$$

$$R_s = \frac{62.5(-2720)^2}{(62.5)^2 + (360)^2} \qquad X_s = \frac{2720\left[(62.5)^2 - 2360(360)\right]}{(62.5)^2 + (360)^2}$$

$$R_s = \frac{62.5(7400000)}{3906 + 129600} \qquad X_s = \frac{2720\left[(3906) - (850000)\right]}{3906 + 129600}$$

$$R_s = \frac{62.5(7400000)}{133500} \qquad X_s = \frac{-2720(846000)}{133500}$$

$$R_s = 3462 \qquad X_s = -17230$$

$$R_p = \frac{(R_s)^2 + (X_s)^2}{R_s} \qquad X_p = \frac{(R_s)^2 + (X_s)^2}{X_s}$$

$$R_p = \frac{(3462)^2 + (-17230)^2}{3462} \qquad X_p = \frac{(3462)^2 + (-17230)^2}{-17230}$$

$$R_p = \frac{12000000 + 296000000}{3462} \qquad X_p = \frac{12000000 + 296000000}{-17230}$$

$$R_p = \frac{308000000}{3462} \qquad X_p = \frac{308000000}{-17230}$$

$$R_p = 88900 \qquad X_p = -17880 \quad \text{or} \quad C_p = 8.90 \text{ mmf}$$

$$\sigma = \frac{0.808}{R_p} \times 10^{-10} \qquad C_t = C_o + \epsilon C$$

$$\sigma = \frac{0.808}{88900} \times 10^{-10} \qquad \epsilon = \frac{C_t - C_o}{C} = \frac{8.90 - 2.81}{1.09}$$

$$\sigma = 9.09 \times 10^{-16} \text{ emu} \qquad \epsilon = \frac{6.09}{1.09} = 5.59$$

TABLE I

CHARACTERISTICS OF THE EMPTY CELL

FREQUENCY MEGACYCLES	C_t MMF	C MMF	C_o MMF
0.6	3.90	1.09	2.81
1.0	3.90	1.09	2.81
2.0	3.90	1.09	2.81
5.0	3.90	1.09	2.81
10.0	3.70	1.09	2.61
20.0	3.70	1.09	2.61
30.0	4.10	1.09	3.01
40.0	3.50	1.09	2.41
50.0	3.20	1.09	2.11

TABLE II

DRY SANDY RED CLAY SOIL

FREQ. MCS.	X_a OHMS	X_e OHMS	R_e OHMS	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵ_c	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	4533.0	3916.7	122.5	27450	6360	28050	124600	9.18	6.37	5.85	6.49
1.0	2720.0	2360.0	62.5	17230	3462	17880	88900	8.90	6.09	5.59	9.09
2.0	1360.0	1200.0	28.0	9870	1965	10270	51500	7.75	5.94	5.45	15.70
5.0	544.0	485.0	9.5	4345	787	4475	24700	7.11	4.30	4.04	32.70
10.0	271.0	244.0	4.3	2381	422	2460	13890	6.47	3.86	3.54	58.20
20.0	134.5	124.0	2.0	1530	316	1595	7720	4.99	2.38	2.18	105.00
30.0	83.3	71.7	1.3	505	66	514	3930	10.33	7.32	6.71	206.00
40.0	57.5	50.0	0.8	375	46	380	3095	10.45	8.04	7.37	261.00
50.0	42.0	38.0	0.2	399	34	402	4670	7.51	5.40	4.96	177.00

TABLE III

DRY RED CLAY SOIL

FREQ. MCS.	X_a OHMS	X_e OHMS	R_e OHMS	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵ_C	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	4533.0	2433.0	972.0	3520	3935	7920	7080	33.50	30.69	28.20	114.0
1.0	2720.0	1650.0	505.0	2940	2670	5760	5900	29.70	26.89	24.70	137.0
2.0	1360.0	925.0	208.0	2100	1655	3405	4320	23.37	20.56	18.90	187.0
5.0	544.0	410.0	64.0	1253	857	1840	2090	17.30	14.49	13.30	300.0
10.0	271.0	216.0	24.5	842	496	1135	1926	14.02	11.41	10.50	420.0
20.0	132.5	112.5	13.0	485	401	917	980	9.74	7.13	6.54	818.0
30.0	83.3	65.3	8.0	238	143	324	540	16.36	10.35	9.49	1500.0
40.0	57.5	47.5	5.0	207	122	278	474	14.31	11.30	10.40	1705.0
50.0	41.0	35.0	2.0	206	84	241	590	13.21	11.10	10.20	1370.0

TABLE IV

MOIST RED CLAY SOIL

FREQ. MCS.	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵC MMF	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	158.3	535.0	1970.0	581.0	134.60	131.79	121.0	1390.0
1.0	184.0	480.0	1438.0	551.0	110.80	107.99	99.1	1470.0
2.0	200.5	382.0	922.5	489.0	86.25	83.44	76.5	1650.0
5.0	196.0	234.0	475.0	398.0	67.00	64.19	58.9	2030.0
10.0	168.0	137.5	280.5	343.0	56.70	54.09	49.6	2360.0
20.0	122.5	75.0	168.4	275.5	47.25	44.64	41.0	2935.0
30.0	73.3	60.0	122.5	149.6	43.30	40.29	37.0	5400.0
50.0	52.0	27.0	66.0	127.1	48.20	46.09	42.3	6350.0

TABLE V

MOIST MEADOW TOPSOIL

FREQ. MCS.	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵC MMF	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	640	1300.0	3140	1546	84.5	81.69	75.0	523
1.0	621	1200.0	2920	1520	54.5	51.69	47.4	532
2.0	598	1003.0	2267	1360	25.1	22.29	20.5	594
5.0	540	540.0	1080	1080	29.6	26.79	24.6	749
10.0	480	390.0	797	981	20.0	17.37	15.9	824
20.0	343	175,5	433	845	18.4	15.79	14.5	956
30.0	210	105.0	263	525	20.2	17.19	15.7	1540
40.0	142	74.6	182	345	21.9	19.49	17.9	2340
50.0	108	51.0	132	280	24.1	21.99	20.1	2890

TABLE VI

DRY MEADOW TOPSOIL

FREQ. MCS.	X_a OHMS	X_e OHMS	R_e OHMS	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵC MMF	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	4533.0	3983.0	85.0	32000	5640	33000	187100	8.03	5.22	4.79	4.31
1.0	2720.0	2400.0	50.0	19360	3530	19980	109500	7.97	5.16	4.73	7.38
2.0	1360.0	1205.0	23.5	10310	1770	10610	61900	7.50	4.69	4.30	13.05
5.0	544.0	490.0	8.5	4800	841	4950	28250	6.44	3.63	3.33	28.60
10.0	270.0	244.0	3.5	2485	371	2535	17000	6.28	3.67	3.37	47.50
20.0	130.0	117.5	1.5	1203	160	1224	9210	6.50	3.89	3.57	87.70
30.0	85.3	77.7	0.5	860	62	864	12050	6.14	3.13	2.87	67.10
40.0	57.5	51.5	-	494	-	494	-	8.55	6.14	5.63	-
50.0	39.0	35.0	-	341	-	341	-	9.32	7.21	6.62	-

TABLE VII

DRY MEADOW TOPSOIL WITH ROCK CHIPS

FREQ. MCS.	X_a OHMS	X_e OHMS	R_e OHMS	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵC MMF	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	4516.7	4016.7	65.0	35650	5215.0	36350	248500	7.30	4.49	4.12	3.25
1.0	2720.0	2420.0	37.5	21550	3040.0	22050	156400	7.21	4.40	4.04	5.17
2.0	1360.0	1220.0	18.0	10430	1670.0	10680	66750	7.45	4.64	4.26	12.10
5.0	544.0	492.0	6.5	5060	700.5	5150	37200	6.18	3.37	3.09	21.70
10.0	271.0	247.0	3.0	3005	375.5	3050	24420	5.22	2.61	2.40	33.10
20.0	130.0	121.0	1.0	1725	206.0	1745	14600	4.56	1.95	1.79	55.40
30.0	85.3	78.7	0.3	982	48.8	985	19700	5.38	2.37	2.17	41.00
40.0	57.5	52.5	-	604	-	604	-	6.60	4.19	3.85	-
50.0	39.0	35.5	-	396	-	396	-	8.04	5.93	5.43	-

TABLE VIII

DRY CORN FIELD TOPSOIL

FREQ.	X_a	X_e	R_e	X_s	R_s	X_p	R_p	C_p	ϵC	ϵ	$\sigma \times 10^{-16}$
MCS.	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	MMF	MMF		EMU
0.6	4541.7	4150.0	18.0	48000	2420.0	48150	955000	5.50	2.69	2.47	0.85
1.0	2725.0	2480.0	10.2	27560	1260.0	27650	604000	5.75	2.94	2.70	1.34
2.0	1362.4	1245.0	5.0	15550	723.0	15650	336500	5.08	2.27	2.08	2.40
5.0	546.0	496.0	2.1	5410	250.0	5420	117300	5.87	3.06	2.81	6.88
10.0	271.0	248.0	1.0	2920	140.5	2925	60800	5.44	2.83	2.60	13.30
20.0	132.5	115.0	0.5	868	28.6	868	26400	9.17	6.56	6.01	30.60
30.0	85.0	76.7	0.2	785	21.0	785	29350	6.76	3.75	3.44	27.50
40.0	57.5	53.8	-	824	-	824	-	4.82	2.41	2.21	-
50.0	39.0	35.8	-	436	-	436	-	7.30	5.19	4.76	-

TABLE IX

DRY FOREST TOPSOIL

FREQ. MCS.	X_a OHMS	X_e OHMS	R_e OHMS	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵC MMF	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	4533.3	4083.3	36.0	48250	3630.0	48500	645000	5.47	2.66	2.44	1.25
1.0	2720.0	2460.0	20.5	22300	2209.0	22500	227200	7.07	4.26	3.91	3.56
2.0	1360.0	1235.0	9.5	13330	1118.0	13410	160100	5.93	3.12	2.86	5.05
5.0	544.0	496.0	3.2	4640	280.5	4660	77100	6.82	4.01	3.68	10.50
10.0	271.0	248.0	1.5	2915	207.5	2925	41100	5.44	2.83	2.60	19.70
20.0	132.5	121.5	0.8	1456	111.0	1462	19180	5.44	2.83	2.60	42.10
30.0	80.0	73.3	0.3	874	42.7	877	17830	6.05	3.04	2.79	45.30
40.0	55.0	50.0	-	550	-	550	-	7.24	4.83	4.43	-
50.0	39.0	36.0	-	468	-	468	-	6.80	4.69	4.30	-

TABLE X

DRY TOPSOIL

FREQ. MCS.	X_a OHMS	X_e OHMS	R_e OHMS	X_s OHMS	R_s OHMS	X_p OHMS	R_p OHMS	C_p MMF	ϵC MMF	ϵ	$\sigma \times 10^{-16}$ EMU
0.6	4533.3	4067.0	54.0	39000	5030.0	39600	307500	6.70	3.89	3.57	2.63
1.0	2720.0	2450.0	35.5	24240	3540.0	24750	169700	6.43	3.62	3.32	4.76
2.0	1355.0	1225.0	16.5	12550	1764.0	12800	91000	6.43	3.40	3.12	8.88
5.0	542.0	492.0	6.0	5250	695.0	5350	40400	6.21	3.14	2.88	20.00
10.0	270.0	244.0	3.0	2497	319.0	2538	19850	5.95	3.66	3.36	40.70
20.0	125.0	112.5	1.5	1107	148.0	1126	8415	6.27	4.45	4.08	96.00
30.0	83.3	76.7	0.9	926	136.0	946	6445	7.06	2.59	2.38	125.50
40.0	55.0	50.0	0.6	542	71.6	552	4175	5.60	4.79	4.40	193.50
50.0	39.0	34.0	0.3	373	15.2	379	9310	7.20	6.29	5.77	86.80

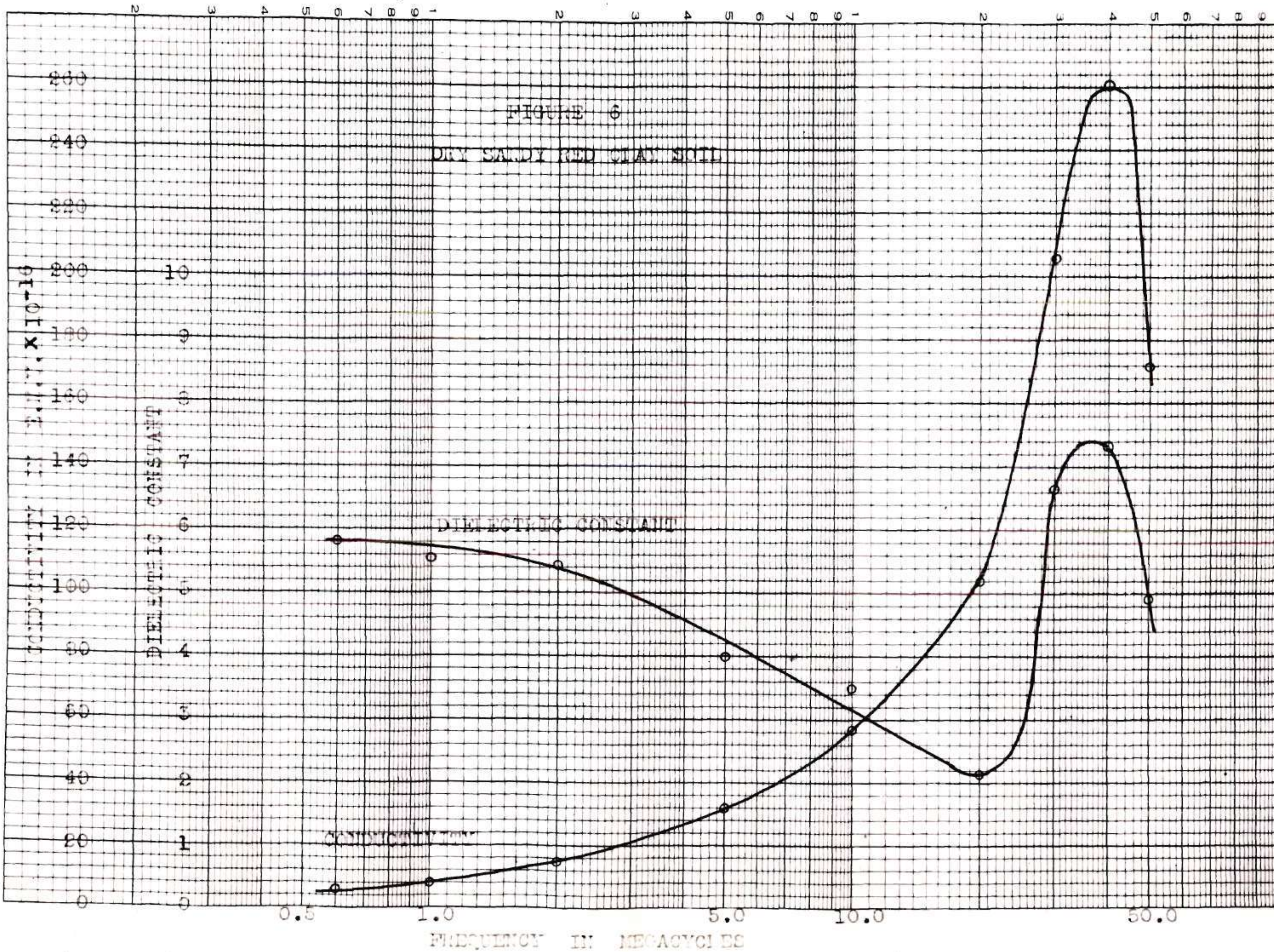


FIGURE 6
DRY SANDY RED CLAY SOIL
DIELECTRIC CONSTANT
CONDUCTIVITY
DIELECTRIC CONSTANT
CONDUCTIVITY IN E.S.U. X10-10
FREQUENCY IN MEGACYCLES
0.5
1.0
5.0
10.0
50.0

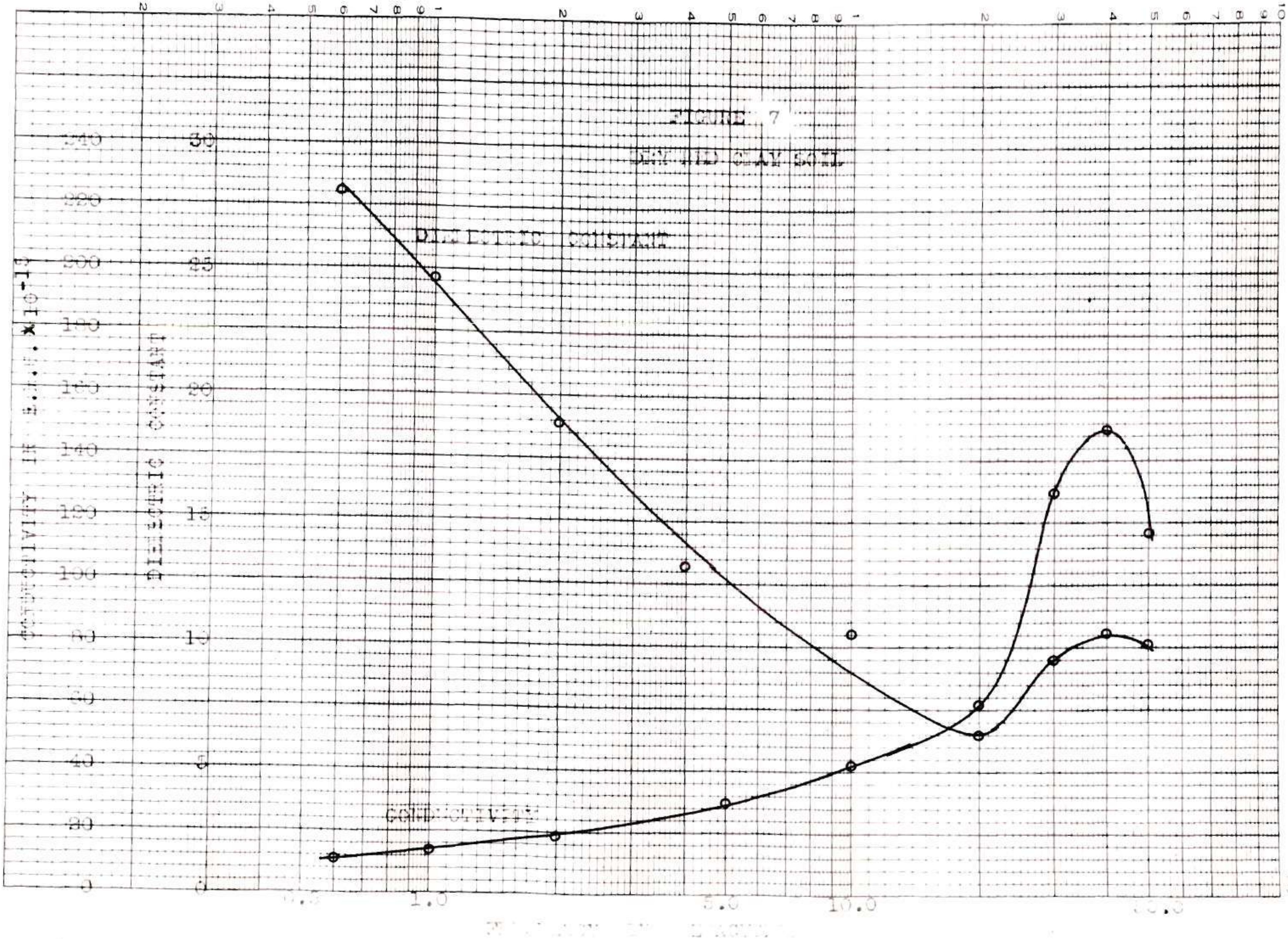


FIGURE 7
DRY RED CLAY SOIL
DIELECTRIC CONSTANT
CONDUCTIVITY
DIELECTRIC CONSTANT
240
220
200
180
160
140
120
100
80
60
40
20
0
30
25
20
15
10
5
0
1.0
5.0
10.0

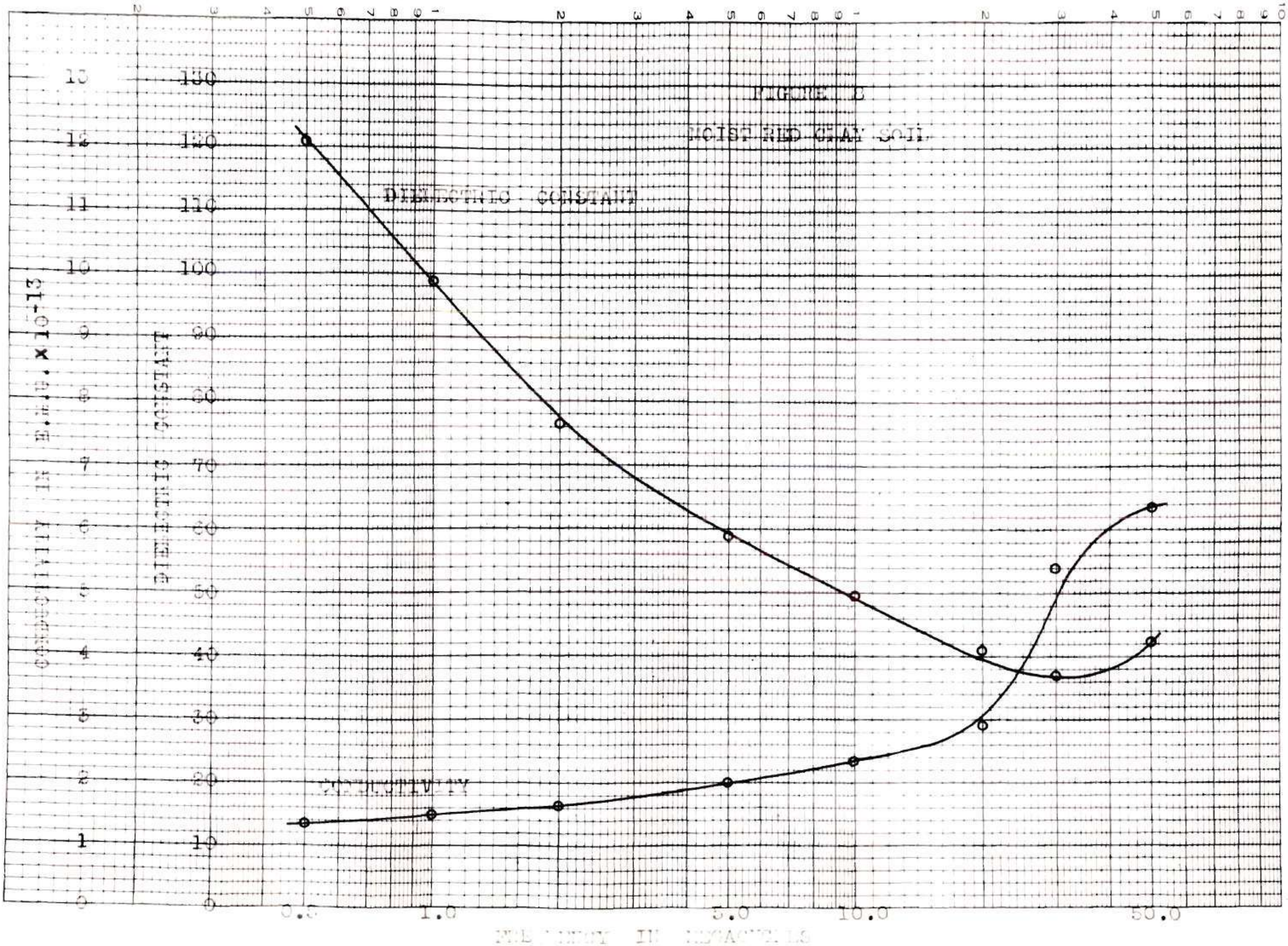


FIGURE 8
MOIST RED CLAY SOIL
DIELECTRIC CONSTANT
CONDUCTIVITY
CONDUCTIVITY IN E.M.U. x 10-13
DIELECTRIC CONSTANT
FREQUENCY IN MEGACYCLES
0.5
1.0
5.0
10.0
50.0

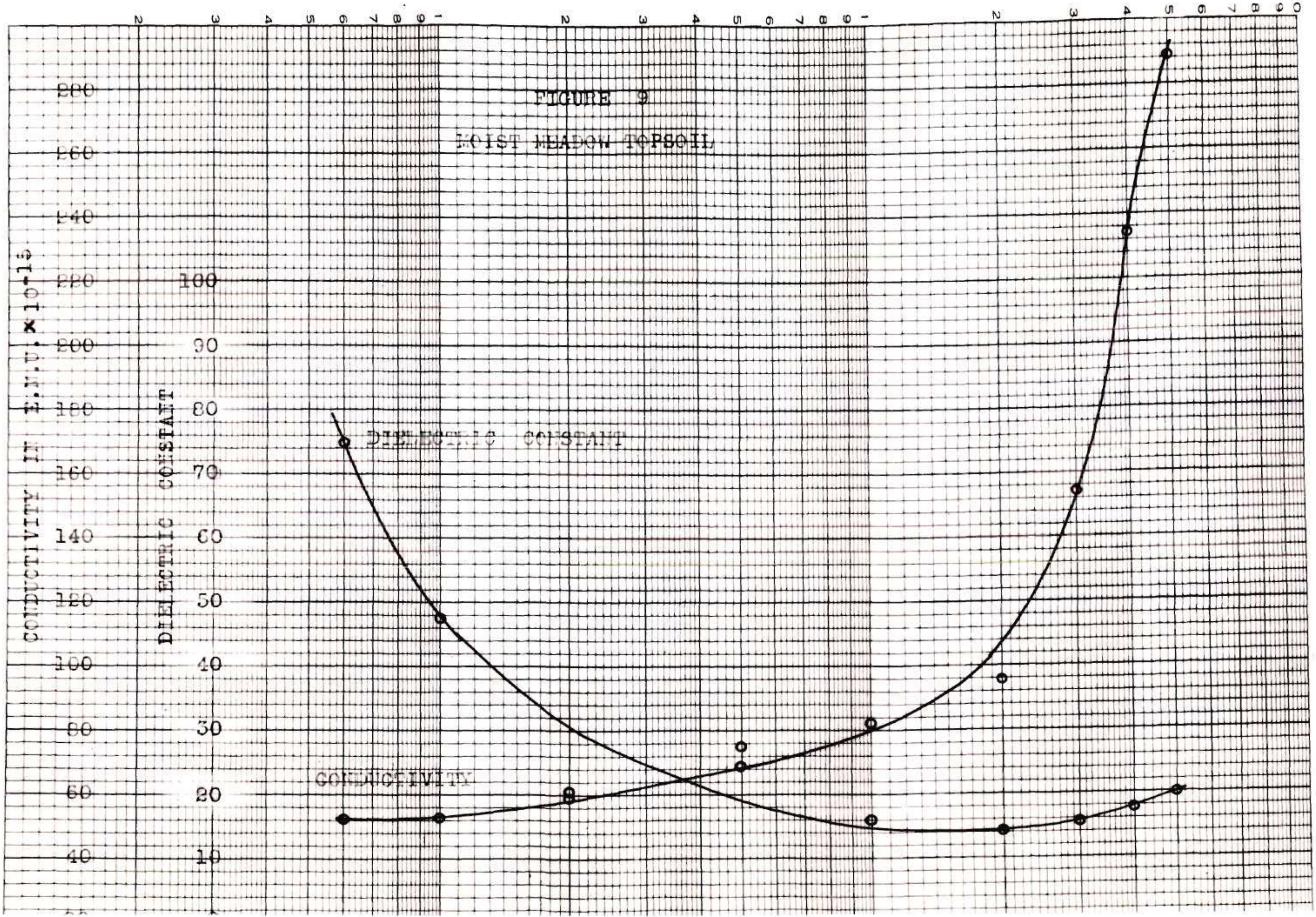
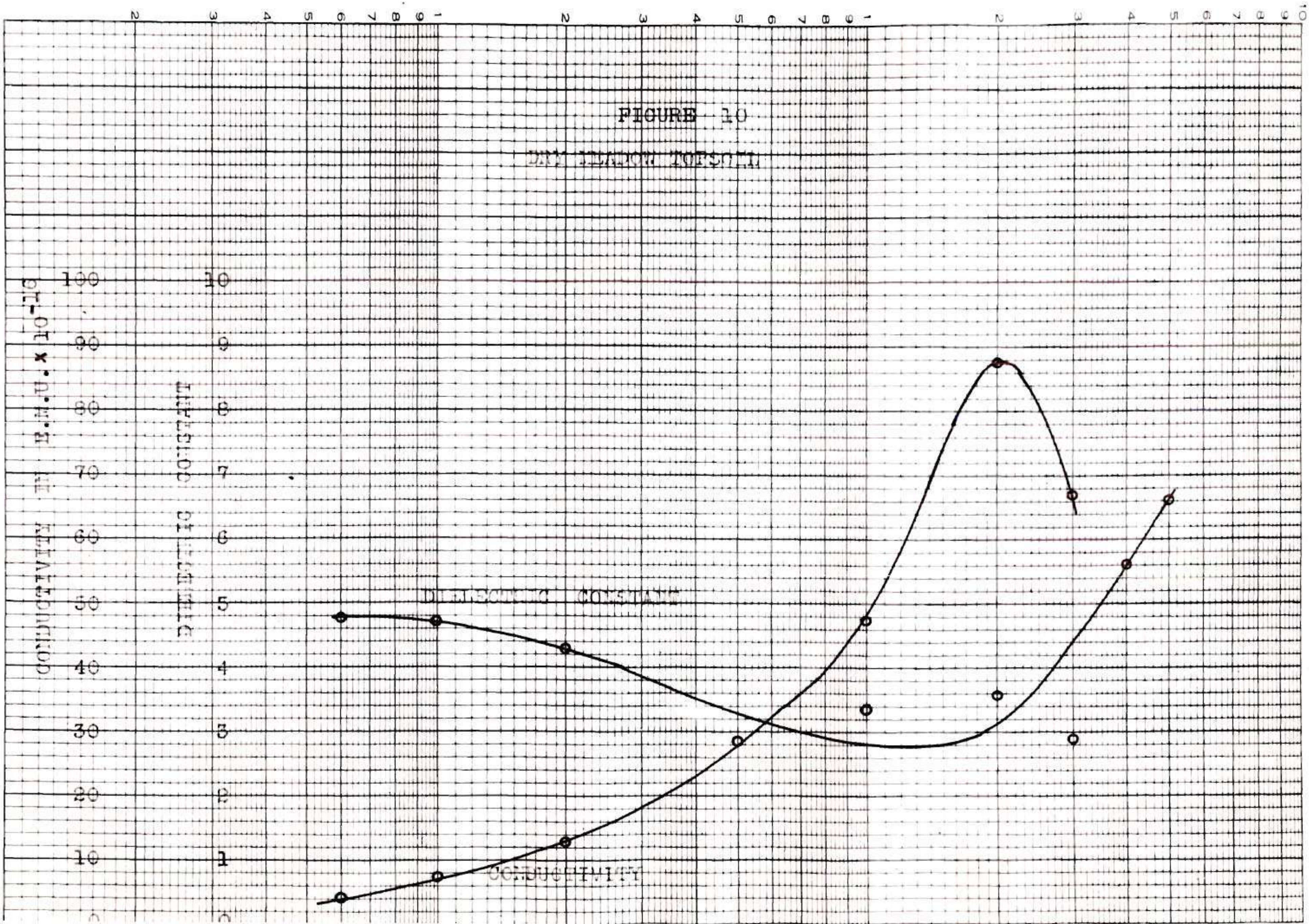


FIGURE 9

MOIST MEADOW TOPSOIL



CONDUCTIVITY IN E.M.U. x 10^{-10}
DIELECTRIC CONSTANT
CONDUCTIVITY

FIGURE 10

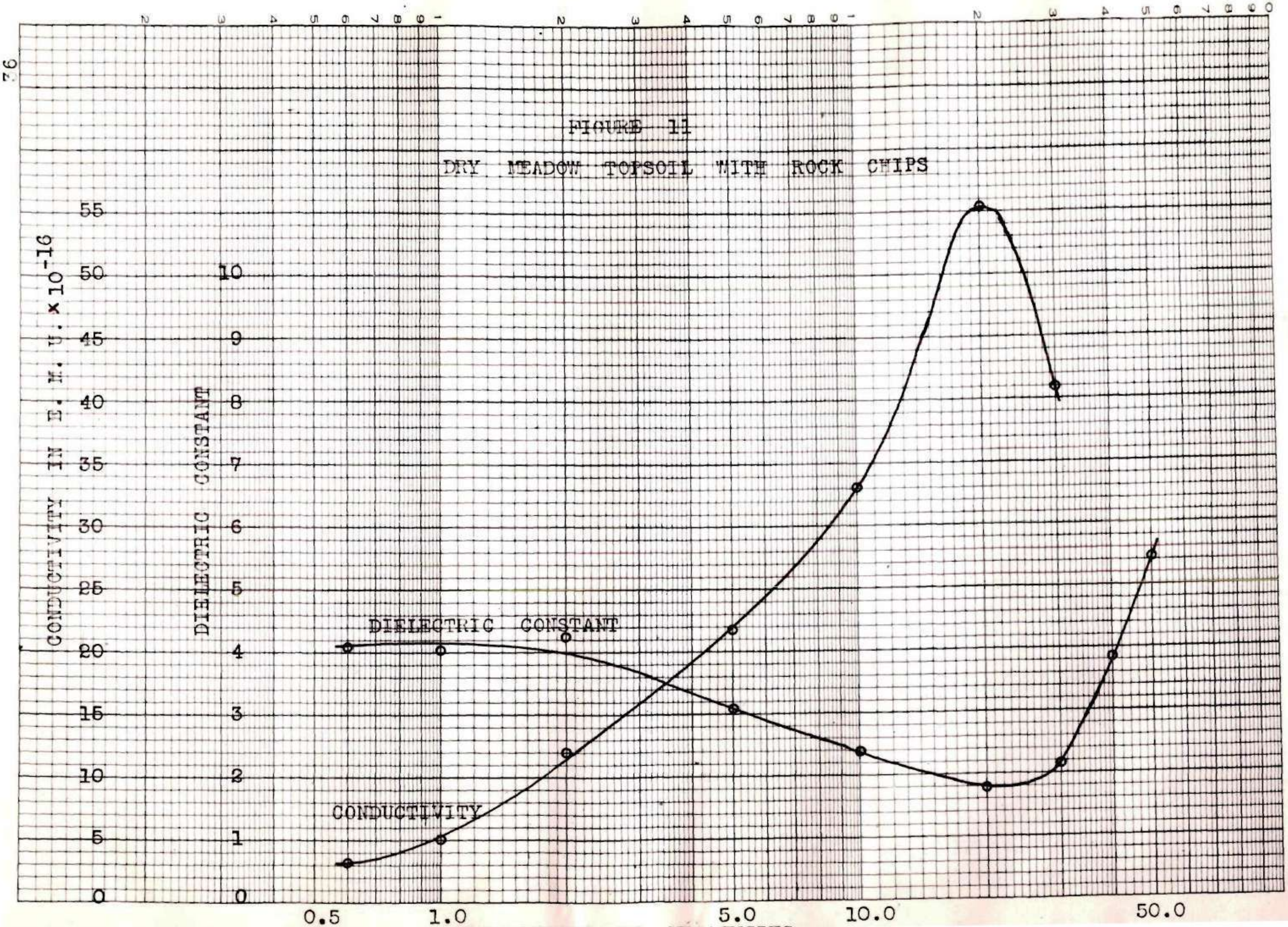


FIGURE 11
DRY MEADOW TOPSOIL WITH ROCK CHIPS
CONDUCTIVITY IN E. M. U. x 10^{-16}
DIELECTRIC CONSTANT
DIELECTRIC CONSTANT
CONDUCTIVITY
55
50
45
40
35
30
25
20
15
10
5
0
10
9
8
7
6
5
4
3
2
1
0
0.5
1.0
5.0
10.0
50.0

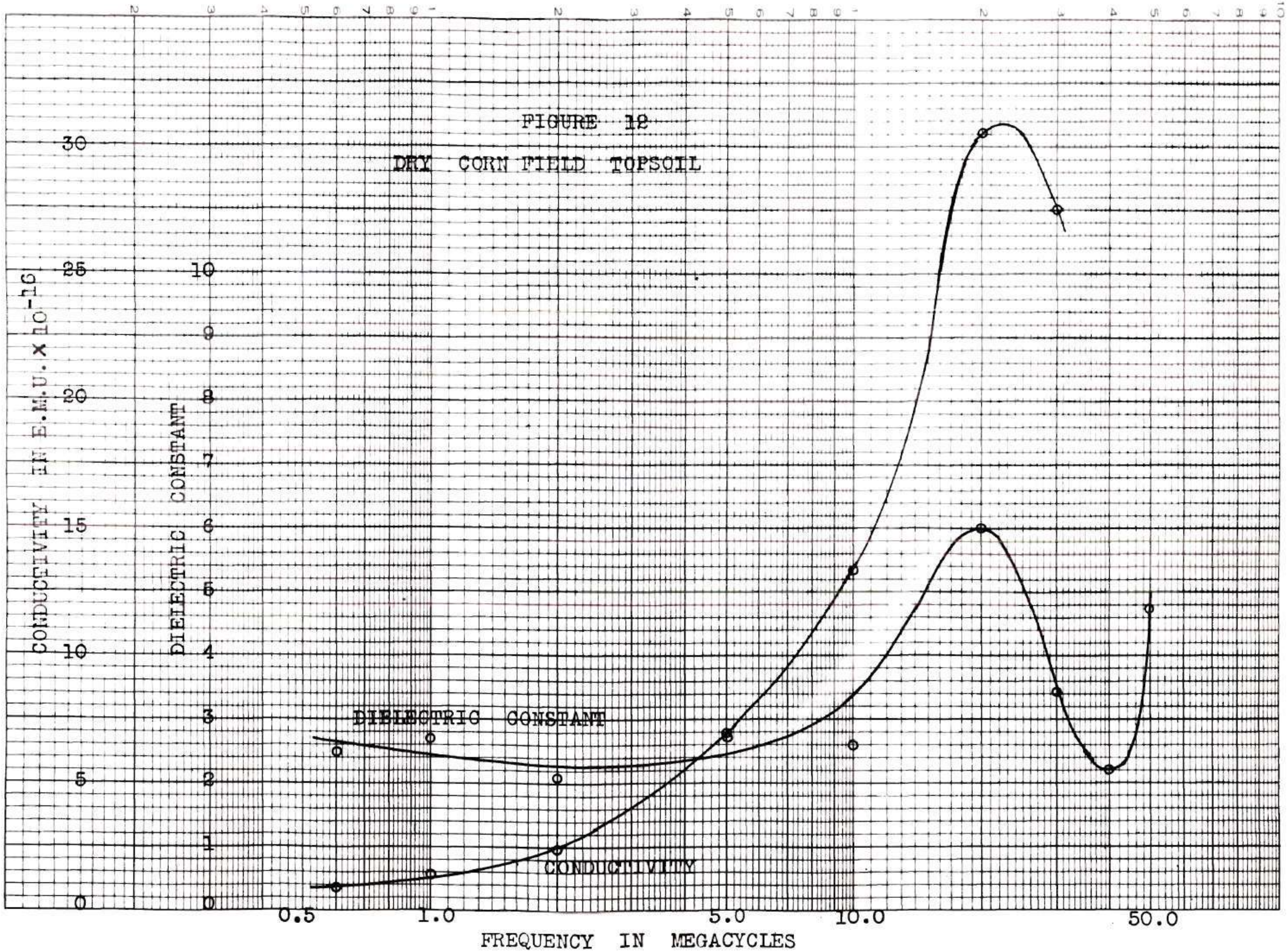


FIGURE 12
DRY CORN FIELD TOPSOIL
CONDUCTIVITY IN E.M.U. X 10^{-16}
DIELECTRIC CONSTANT
DIELECTRIC CONSTANT
CONDUCTIVITY
FREQUENCY IN MEGACYCLES
0.5
1.0
5.0
10.0
50.0
0
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8
9
10

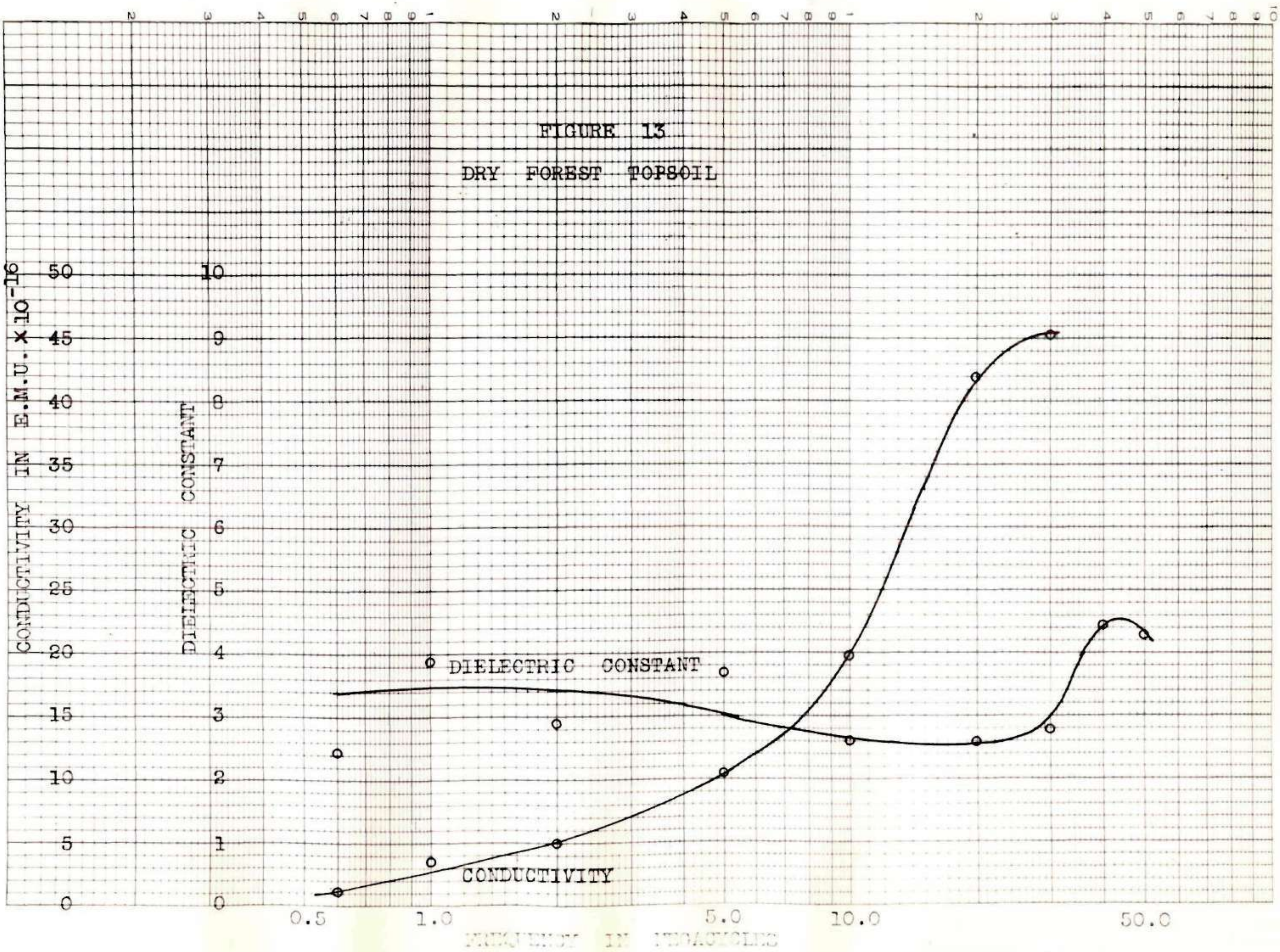


FIGURE 13

DRY FOREST TOPSOIL

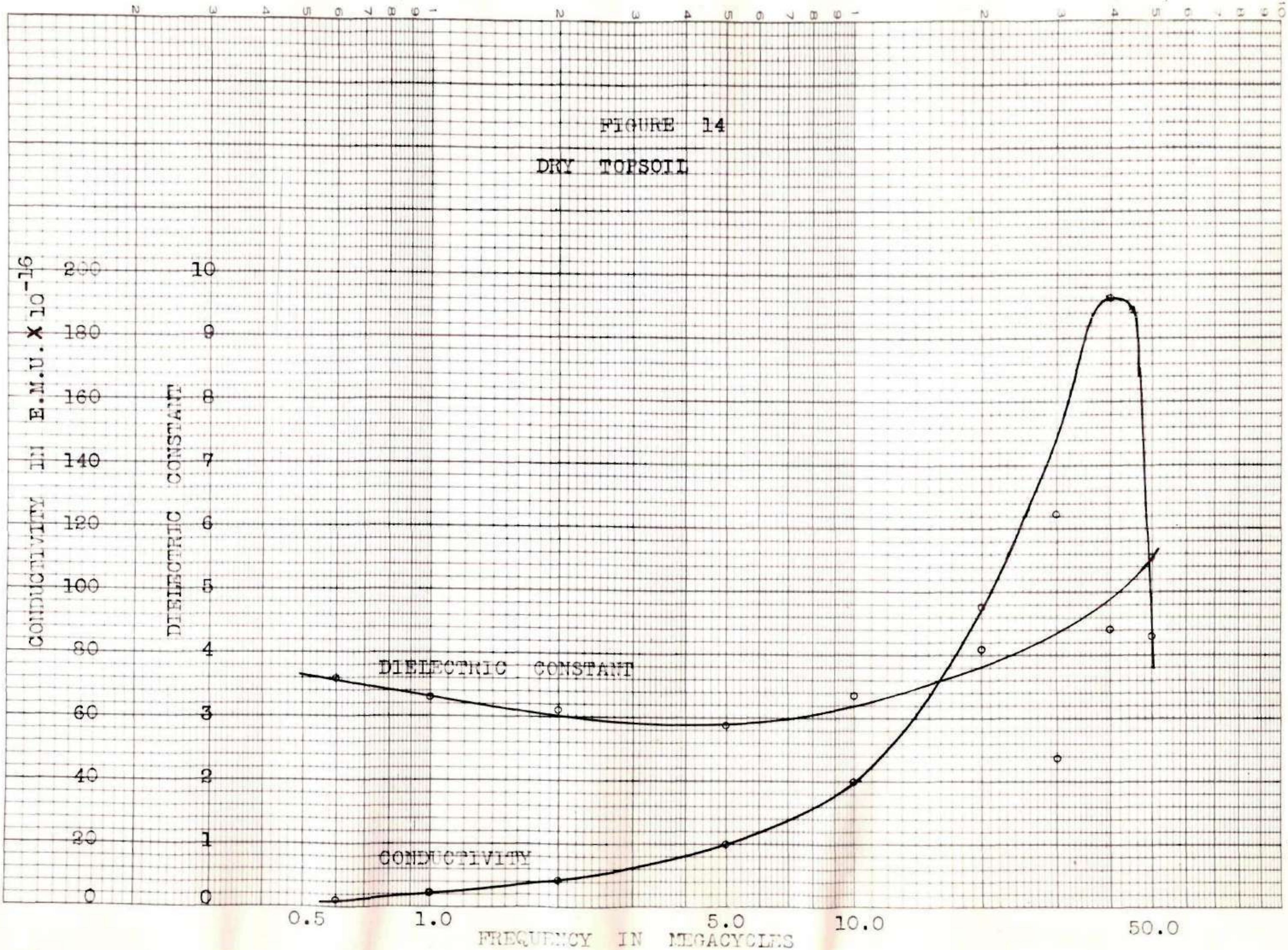


FIGURE 14

DRY TOPSOIL

CONCLUSIONS

It was noted that determinations of conductivity and dielectric constant became exceedingly difficult at the higher frequencies. Although this has partially been explained in the preceding pages, a further explanation may be found in the work of R. L. Smith-Rose.[6] For the higher frequencies the physical dimensions and capacitance of the concentric cylindrical condenser make its use difficult at frequencies above ten megacycles. It is believed, that at these higher frequencies, the inductance and skin effect of the cell and sample become a source of error, since no effort was made to account for them in this work. This line of reasoning may be used to explain the peculiarities of the curves for the conductivity and dielectric constant at these frequencies. Although the curves for the conductivity seem fairly regular, the "hump" in the curves for the dielectric constant seem singularly odd. It may be that the dielectric constant should vary in such a manner (note rise at 30 mcs. in Figures 5 - 15), but it is hardly logical to assume so without further proof. A partial explanation of this peculiarity may be found in Hartshorn's work. "The effect of the self-inductance of a condenser is to cause

[6] R. L. Smith-Rose, "The Electrical Properties of Soil at Frequencies up to 100 mc. with a Note on the Resistivity of Ground in the United Kingdom", The Proceedings of the Physical Society, Vol. 47, 1935, p. 924.

the effective capacitance to increase with a rise in frequency. This inductance may vary with frequency on account of eddy currents or skin effect."[7] "The capacitance of a condenser may diminish with a rise in frequency owing to dielectric absorption in any solid dielectric, which may be present, and that it may increase with a rise of frequency owing to the inductance of the plate systems. The latter effect usually predominates. The inductance of two coaxial tubes will diminish as the diameter becomes larger and the radial spacing between the tubes becomes smaller."[8] This view, however, opens a new field of investigation which will not be discussed at length here. Since the concentric cylindrical condenser used in this treatment is essentially a short length of coaxial transmission line, it is logical to assume that it has a certain inductance and that this inductance, together with the inductance of the banana-plug leads, and the skin effect at the high frequency might give such an effect. There is also the possibility that some sort of resonance condition might explain this unusual variation of the dielectric constant. Since a different signal generator was used at the higher frequencies, it is thought that its output voltage might have been different than that of the

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[7]L. Hartshorn, Radio Frequency Measurements by Bridge and Resonance Methods. New York: John Wiley and Sons, Inc., 1941. p. 120.

[8]Ibid. p. 178.

other one and allow an error due to the voltage sensitivity of the cell to creep in. It was noted that the output of this second signal generator had a tendency to be unstable.

The results of this work are believed to be within an accuracy of twenty percent (at least for frequencies less than 30 mcs.), and, since an accuracy of twenty percent is considered adequate for measurements of soil, the discrepancies noted were not investigated further, but were merely set down as interesting and matters for further study. It seems reasonable that false effects might be observed at the higher frequencies. To be absolutely certain of the reality of these apparent variations would require check measurements made with totally different apparatus, with which the unknown false effects would likely be different or occur at a different frequency.

It is believed that greater accuracy would be obtained if the need for the auxiliary condenser could be eliminated. This might be achieved by using a cell of different physical dimensions. An increase in the radius of the inner conductor would increase the capacitance of the cell and gain this end The use of a Q-meter or resonance method of measurement rather than the bridge method might increase the accuracy..

The increase of conductivity and thedecrease of dielectric constant as the frequency increased is believed to be real. This is in agreement with the work done by Feldman and Smith-Rose. The conductivity and dielectric constant were both found to be very dependent upon the moisture content of the soil. The effect of frequency on conductivity was more marked for dry soil than for moist soil, whereas the converse is true for the dielectric constant.

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APPENDIX

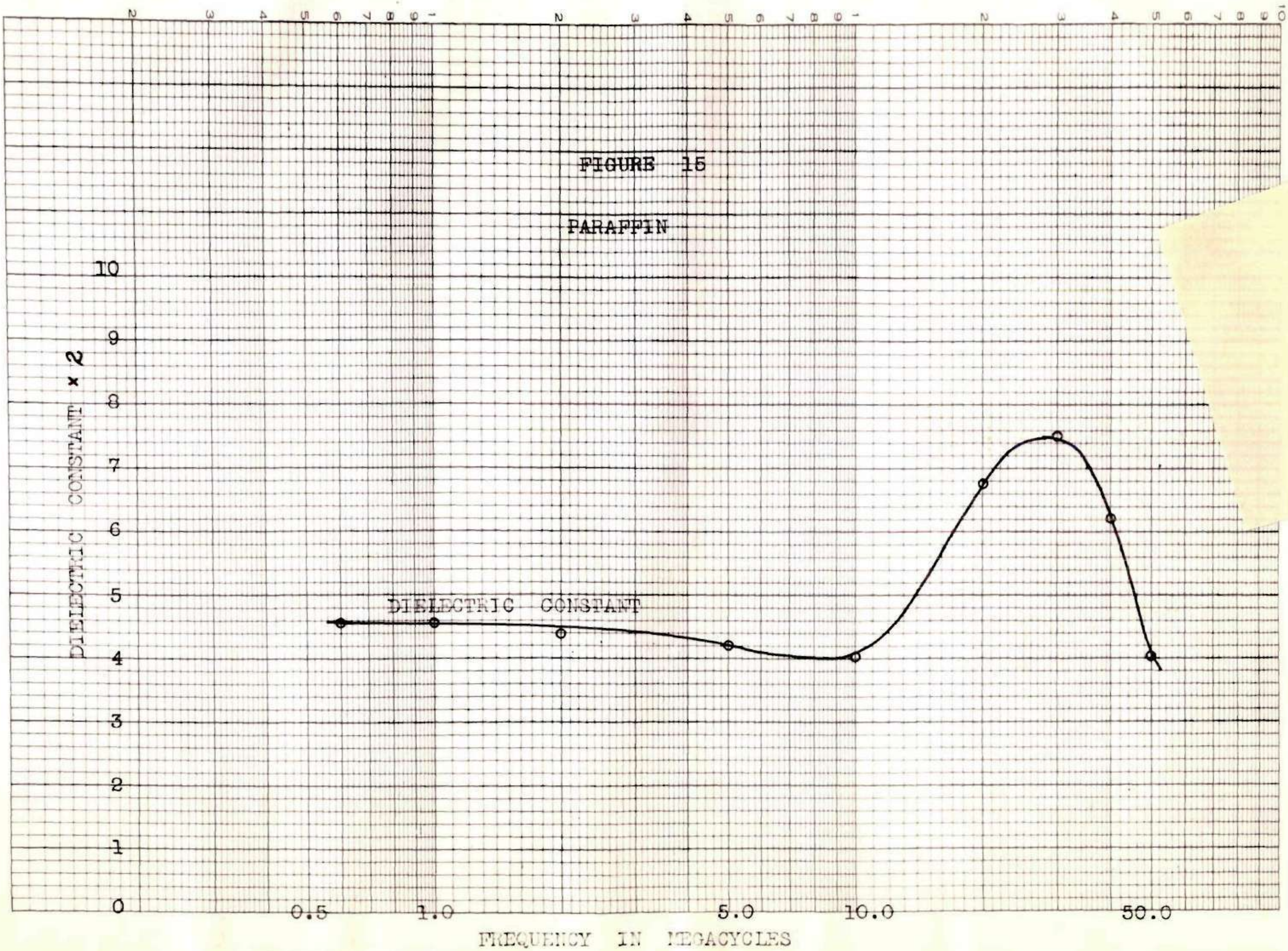
CHECK MEASUREMENTS

Before measurements were actually made to determine the electrical properties of soil, a series of measurements were made to check the validity of the method to be used. Quite a number of these measurements were made so that the author could improve his technique as well. Since brevity demands, only a few of these checks have been included in this appendix. The first of these was simply a series of measurements to determine the dielectric constant of a known dielectric. A curve has been plotted showing the variation of the dielectric constant of paraffin, as determined by these measurements. Since we know that the dielectric constant varies between two and five, this curve seems to indicate that the technique used to obtain it was reasonably good.

Another check was made by measuring various series and parallel combinations of standard resistors and condensers, using two bridges so as to check one against the other. Only one example of such measurements is discussed here. In this case an effort was made to simulate the earth cell by using a parallel arrangement of two 15mmf condensers and a 10,000 ohm resistor. These three elements were connected in parallel, and measurements were made with both bridges. The results are shown for a frequency of one megacycle. Using the General Radio Bridge, type 516-6, the following measurements were obtained with the power factor dial

FIGURE 15

PARAFFIN



set at 0.06 percent, which is the power factor of the standard condenser (100 mmf) at this frequency. This standard condenser was used as an auxiliary capacitor.

$C' =$	102.2 mmf	Capacitance of the standard
$C =$	134.9 mmf	Capacitance of the unknown and the standard in parallel
$R' =$	0.0 ohms	Resistance of the standard only
$R =$	152.1 ohms	Resistance of the unknown and the standard in parallel

Using the formulas given in the operating instructions for the type 516-C bridge and those previously derived, the following results were obtained.

$$X_p = 5340 \text{ ohms} \quad C_p = 29.8 \text{ mmf} \quad R_p = 10100 \text{ ohms}$$

Using the General Radio Bridge, type 916-A, the following measurements were made.

$X_o = 4000$	$R_o = 0$	Initial balance
$X_1 = 1300$	$R_1 = 0$	Balance using 50mmf standard
$X_2 = 2200$	$R_2 = 300$	Balance with standard and unknown in parallel

From these measured values we obtain the following:

$X_a = 4000 - 1300 = 2700$	Reactance of the standard
$X_e = 4000 - 2200 = 1800$	Reactance of the standard and unknown in parallel
$R_e = 300$	Resistance of the standard and unknown in parallel

By using the method illustrated in the sample calculations in the text, the following results were obtained.

$$X_p = 5875 \quad C_p = 27.1 \text{ mmf} \quad R_p = 11110 \text{ ohms}$$

This check further illustrates the justification of the method used.